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DESIGN AND FABRICATION OF EXPONENTIAL NOZZLE

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This report covers the design and manufacture of an exponential nozzle which is intended for use in experiments on the breakage of rock by high pressure pulsed water jets. The nozzle was designed by Terraspace, based on data obtained from Prof. B. V. Voitsekhovsky in the USSR. It was manufactured by the Speco Division of Kelsey-Hayes Corp. Problems were encountered during manufacture, including inadequate quality of steel and possible stress corrosion or hydrogen embrittlement during assembly. The nozzle as-built is calculated to be able to withstand an internal maximum pressure of 170,000 psi and to be able to produce water jet stagnation pressures up to 680,000 psi through a 6.05 mm (0.238 inch) exit diameter. This report supplements the Annual Report (TR-4032) on Bureau of Mines Contract H0210012, which reports experimental results with an imported Russian nozzle of similar design having a larger exit diameter of 7 mm (0.276 inch).

Details of illustrations in this document may be better studied on microfiche

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SUMMARY

This report covers the design and manufacture of an exponential nozzle which is intended for use in experiments on the breakage of rock by high pressure pulsed water jets. The nozzle was designed by Terraspace, based on data obtained from Prof B. V. Voitsakhovsky in the USSR. It was manufactured by the Speco Division of Kelsey-Hayes Corp. Problems were encountered during manufacture, including inadequate quality of steel and possible stress corrosion or hydrogen embrittlement during assembly. The nozzle as-built is calculated to be able to withstand an internal maximum pressure of 170,000 psi and to be able to produce water jet stagnation pressures up to 680,000 psi through a 6.05 mm (0.238 in) exit diameter.

This report supplements the Annual Report (TR-4032) on Bureau of Mines Contract H0210012, which reports experimental results with an imported Russian nozzle of similar design having a larger exit diameter of 7 mm (0.276 in).

1.0 OBJECTIVES AND SCOPE

The object of the research program was to optimize the efficiency of rock disintegration by pulsed high pressure water jets. The major portions of the experimental program were reported in Annual Report No. TR-4032 (Ref. 1) dated January 1972. This report covers the design and fabrication of the American-made nozzle which was completed in March 1972. (Too late to be tested during the one year program).

The major objectives of the test program were accomplished using a nozzle assembly manufactured in Russia, an adapter section, and Section 1 of the American design nozzle assembly. Sections 2 through 5 of the American design nozzle assembly were completed in March 1972 and have been delivered. Experiments using this nozzle are planned during 1972.

2.0 DESIGN AND MANUFACTURE OF THE NOZZLE

The assembly drawing of the nozzle is shown in Fig. 1.

Fig. 2 is a photograph of the nozzle components prior to press-fit assembly of the double-walled sections (Nos. 3,4,5) and prior to completion of threads on Section 2.

Fig. 3 is a photograph of the nozzle, except for Section 1.

Fig. 4 shows the complete nozzle, installed in the water jet test rig.

The internal dimensions of the American nozzle were made as close as possible to those for a high performance nozzle which had been tested by Prof. Voitsekhovsky. Fig. 5 shows a plot of nozzle diameter vs. distance from the nozzle throat. It is seen that the diameter and therefore the area decrease approximately exponentially from the throat through Section 3. The bore diameters of Sections 4 and 5 are increased slightly from the exponential curve. This permits the final acceleration of water to be somewhat reduced which helps limit the peak wall pressure in the nozzle.

In Sections 2 and 3, the value of the nozzle parameter K is 8 inches (20.3 cm). This is the distance over which the area decreases by a factor of 2.718.

The proper piston mass M to use with the nozzle is found from the relation (Ref. 2):

$$K = \frac{S_0 M}{\rho S_1^{\,2}}$$

where S_0 = throat area

S_1 = piston area

ρ = density of water

For a piston diameter of 3.25 in. (8.25 cm) and a throat diameter of 2.125 in. (5.4cm), the piston mass theoretically should be 2.53 kg (5.55 lb.). However, because of leakage past the piston through the clearance gap, the piston mass should be increased to compensate for energy loss. For a radial gap of 0.020 in., the leakage area is nearly 6% of the nozzle throat area. Assuming energy loss is proportional to leakage area, the piston mass should be increased by 6% to compensate. The piston mass should therefore be approximately 2.7 kg (5.9 lb.).

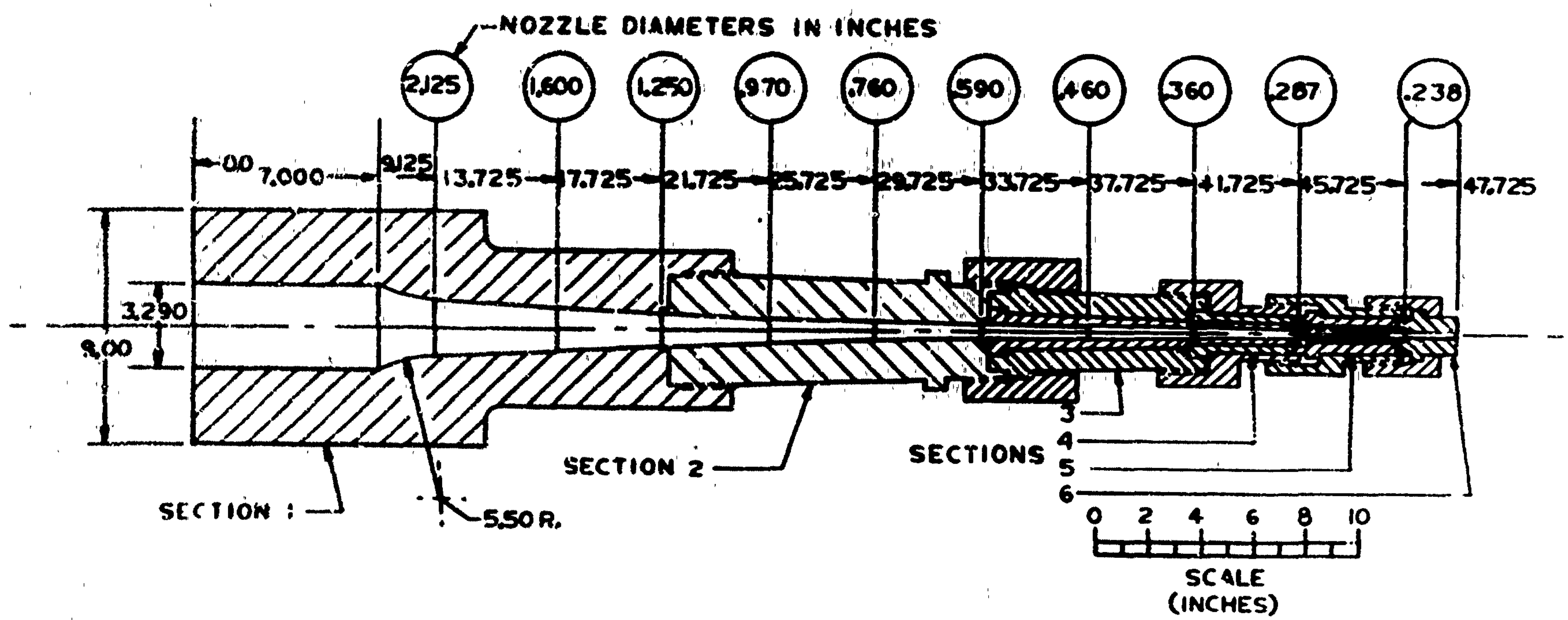

Figure 1. Drawing of American Design Nozzle

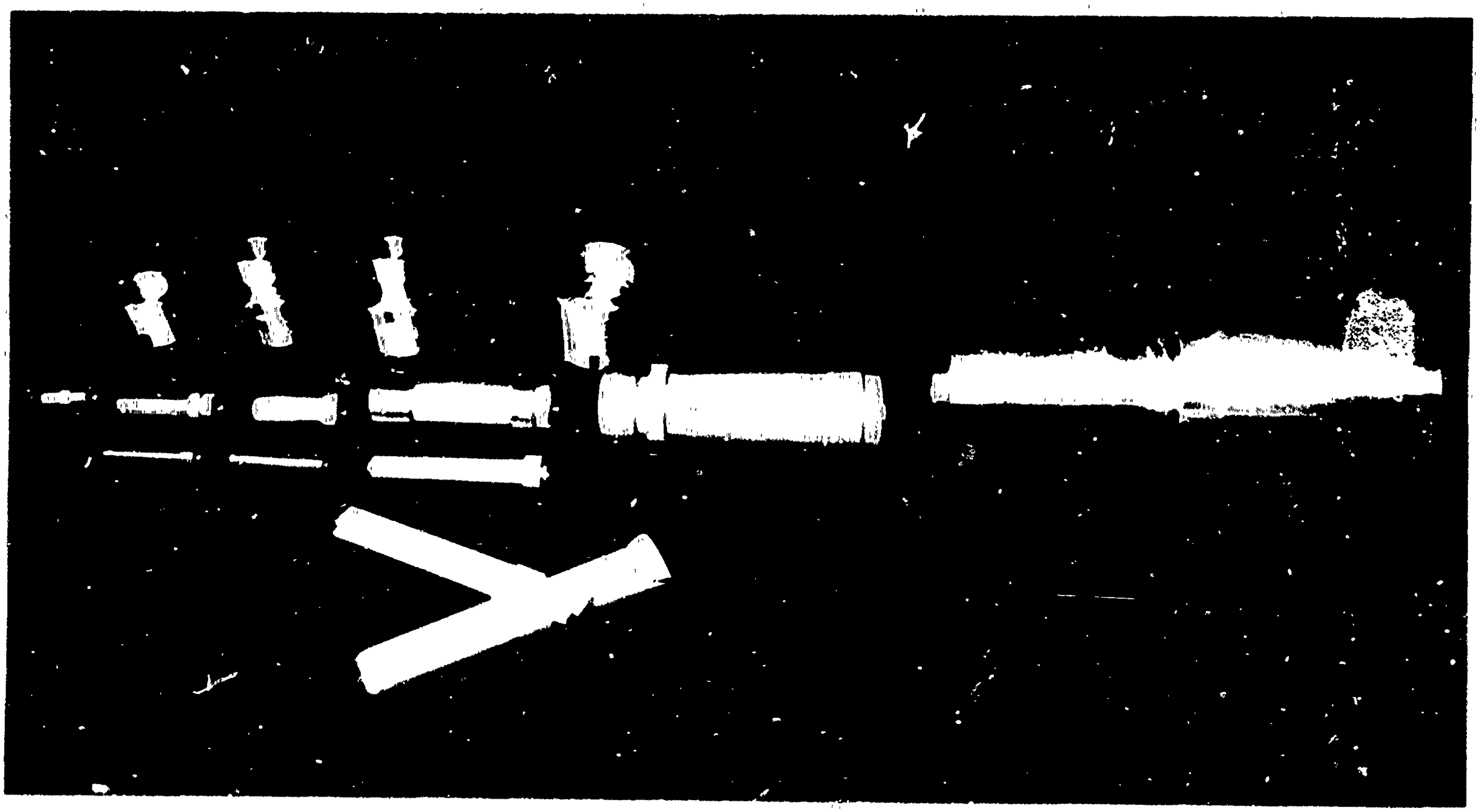

Figure 2. Semi-finished American Nozzle Components

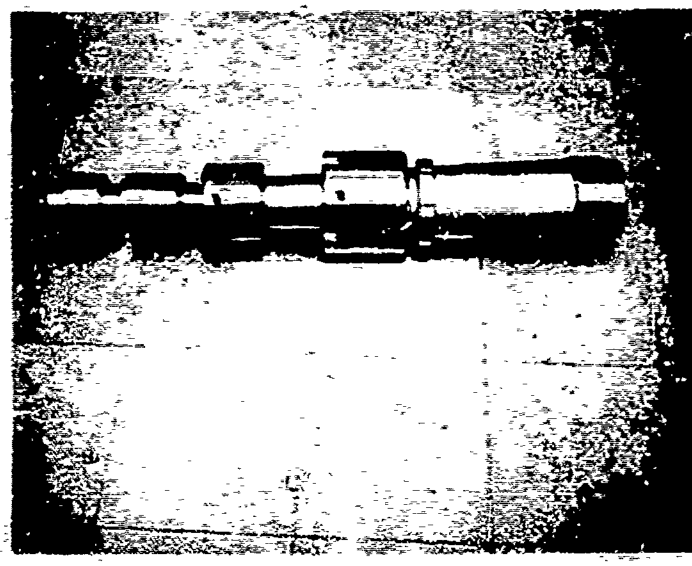

Figure 3. American Nozzle Assembly Without Section 1

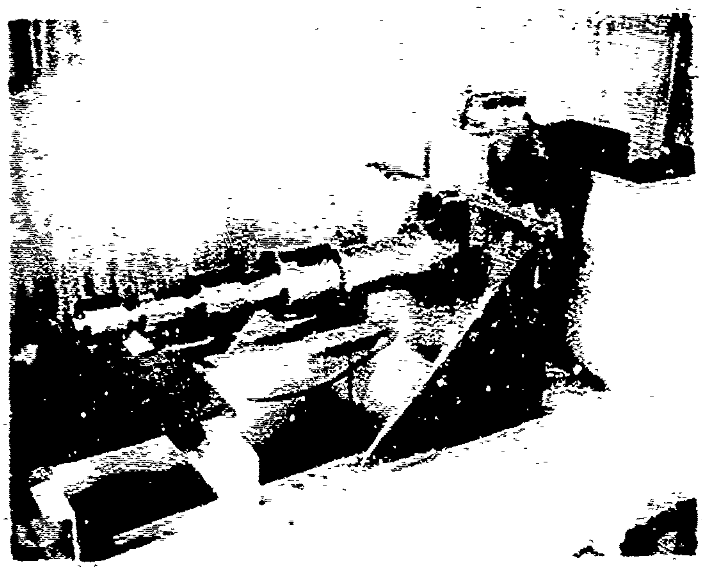

Figure 4. Complete American Nozzle Assembly in Test Rig

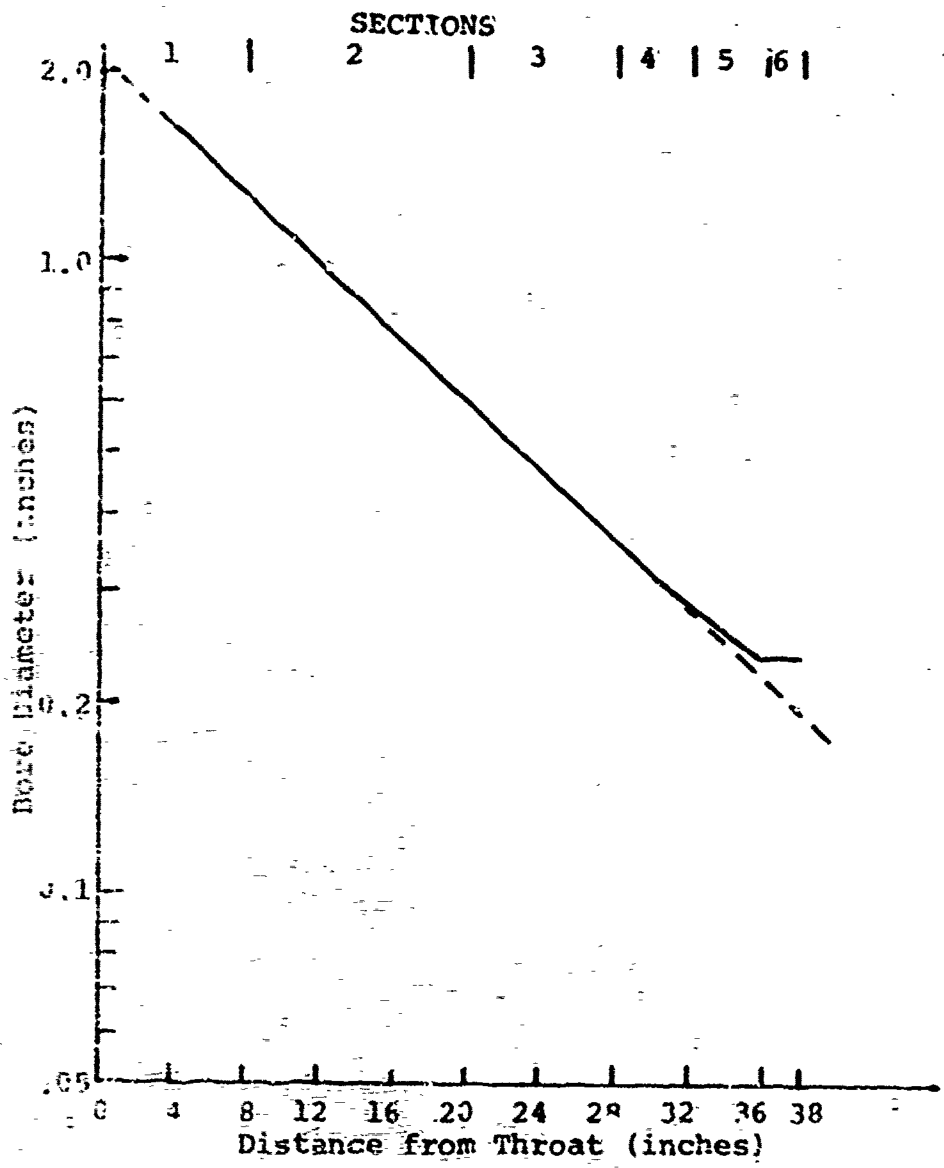

Figure 5. Dimensions of Nozzle

The structural design was based on stress analysis which had been conducted previously by Terraspace and by Pressure Science, Inc. for a larger nozzle which was designed for the U.S. Department of Transportation (Ref.3). The interferences required on the tapered interfaces between the inner and outer sleeves of each nozzle section were reduced from those for the larger nozzle in proportion to the interface diameters. However the interference in Section 4 was reduced by 15%. (See below).

The entrance chamber of the nozzle had a bore diameter of 8.35 cm (3.29 in.) in order to accept pistons of 3.25 in. diameter which are fired from the gas gun. The nominal design point of the nozzle requires a piston velocity of 220 m/sec (720 ft/sec) in order to start filling the nozzle with the same volume flow rate as achieved by Prof. Voitsekhovsky in his tests.

Nozzle Sections 3,4,& 5 were initially designed for a maximum internal pressure of 200,000 psi, which would have permitted attainment of a maximum jet stagnation pressure of 800,000 psi with an exit diameter of 0.605 cm (0.238 in.) The material is AISI 4340, heat treated to a yield strength of 220,000 psi.

Problems were encountered in manufacture of Sections 2 and 4 of the nozzle. During assembly, the outer sleeve of Section 2 failed in tension due to a flaw in the AISI 4340 steel which was used. Inspection prior to assembly failed to detect the flaw. A new part was made and successfully assembled.

The outer sleeve of Section 4 failed several days after pressing together the two sleeves. Inspection by the Battelle Memorial Institute indicated that this failure may have been caused by stress corrosion or hydrogen embrittlement. A new part was made, but it also failed approximately five minutes after assembly. This tensile failure of the outer sleeve appeared to initiate at the exit end, although no flaw could be detected there. The fracture proceeded along the sleeve, passing through a bleed channel where a small radius stress raiser existed.

A third outer sleeve of Section 4 was manufactured with a slight design change to avoid the stress raiser and with a slight decrease in the diametral interference from 5.9 to 5.0 mils. This third sleeve was assembled satisfactorily. It is calculated that Section 4 will withstand a static pressure of approximately 170,000 psi in the critical section. This should permit a jet stagnation pressure of 680,000 psi. During tests, the inside bore diameter at the exit of Section 4 should be measured periodically to determine whether yielding has occurred.

3.0 PERFORMANCE ANALYSIS OF THE NOZZLE

Calculations were performed of the pressure distribution in the nozzle during a pulse and also the maximum pressure in the nozzle as a function of piston velocity. The analyses were made assuming incompressible flow of water using an analytical method provided to Terraspace by Prof. Voitsekhovsky. The method is probably inaccurate in the regions of the nozzle where pressures are from 100,000 to 200,000 psi and water compressibility is significant.

The maximum wall pressure occurs at a point 5.5 inches from the entrance to the collimator, which puts it 1.5 inches from the exit of Section 4.

It seems probable that the calculation method may not be accurate because, when applied to the Russian-made nozzle, the peak pressure was calculated to be 275,000 psi at a water volume flow equivalent to a piston velocity of 720 ft/sec. The nozzle survived the Russian test at a slightly higher volume flow rate without yielding, even though the design pressure as reported by Prof. Voitsekhovsky was only 180,000 psi. Therefore, the incompressible analysis appears to predict an unrealistically high nozzle wall pressure. Both compressibility and the departure of the nozzle shape from exponential should be considered in the analysis.

Fig. 6 shows a plot of the calculated pressure distribution along the length of the nozzle at the instant when the water front leaves the decreasing area section and enters the collimator. This curve is calculated for a piston velocity of 445 ft/sec which gives a predicted peak pressure of 170,000 psi.

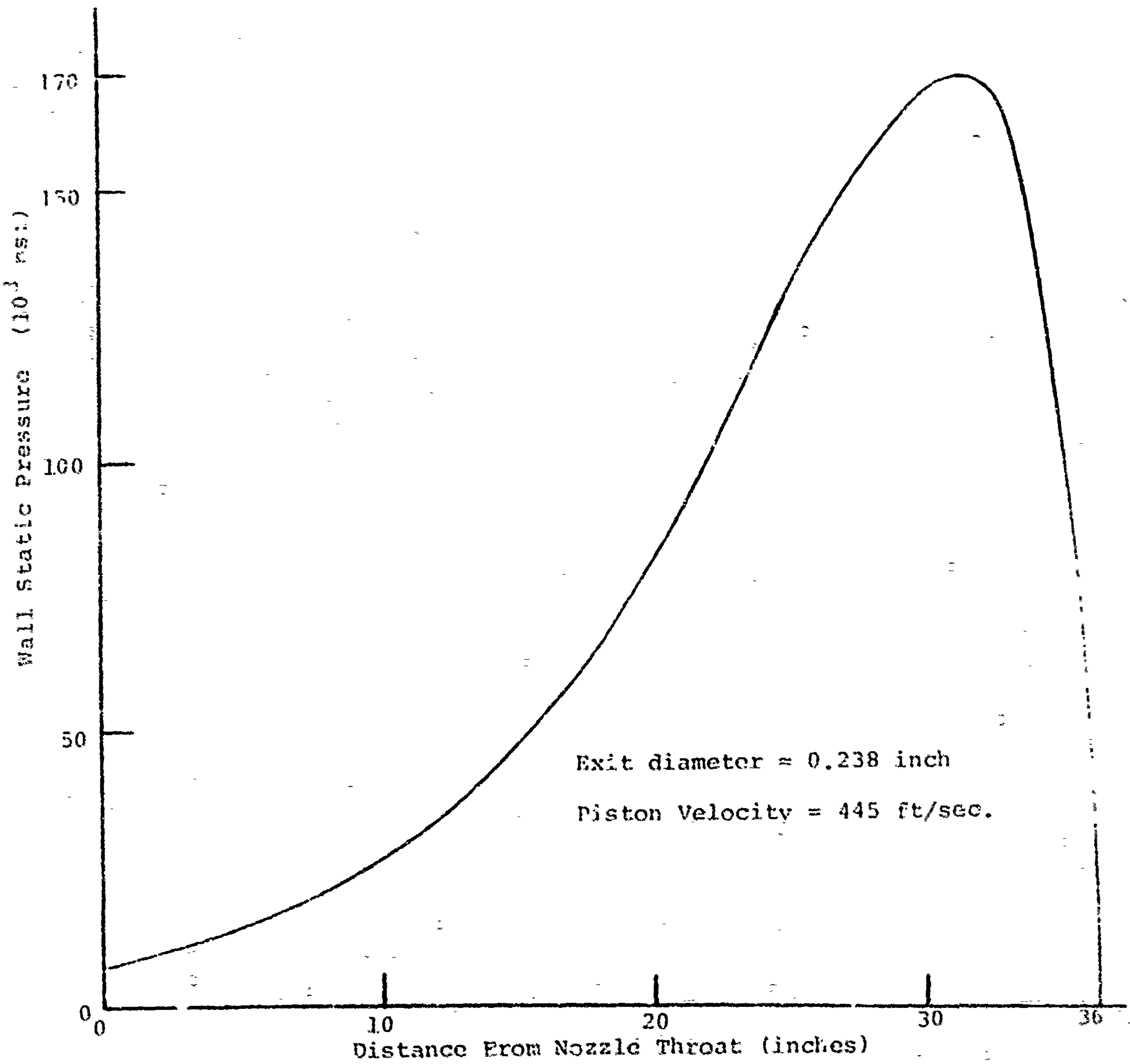

Figure 6. Pressure Distribution in Nozzle at Instant when Water Reaches Collimator

4.0 CONCLUSIONS

As a result of the nozzle design and manufacture, the following conclusions were reached:

1. Commercial grade AISI 4340 steel is inadequate for use in a nozzle of this type because flaws are likely to be present which cannot be detected adequately by magnetic particle or ultrasonic inspection methods. A premium grade steel is necessary.

2. Care must be taken to minimize the effect of hydrogen embrittlement or stress corrosion by lubricant and coolant liquids during manufacturing.

3. The nozzle as manufactured is estimated to be capable of withstanding an internal pressure in the critical Section 4 up to 170,000 psi. This would permit attainment of a jet stagnation pressure up to 680,000 psi.

5.0 RECOMMENDATIONS

1. Future nozzles of this type should use premium grade AISI 4340 steel. The double walled sections should be machined from forged material.

2. Care should be taken in the design to avoid stress concentrations which may be introduced by water bleed channels.

3. Research should be conducted on the effect of lubricants and coolants on stress corrosion and hydrogen embrittlement of high strength alloys like AISI 4340.

4. In order to predict the pressure distribution in a cumulation nozzle of this type, computer analyses should be conducted, taking into account the water compressibility effects and the actual nozzle dimensions which vary from an exponential curve.

REFERENCES

1. Cooley, W.C. & Brockert, P.E., Rock Disintegration by Pulsed Liquid Jets". Report No. TR-4032, Annual Report on Bureau of Mines Contract No. H0210012 by Terraspace Inc. January 31, 1972.

2. Voitsekhovsky, V.V., "Jet Nozzle for Obtaining High Pulse Dynamic Pressure Heads", U. S. Patent No. 3,343,794, September 26, 1967.

3. Cooley, W.C., Beck, F.L. and Jaffe, D.L., "Design of a Water Cannon for Rock Tunneling Experiments", Report No. FRA-RT-71-70 U.S. Dept. of Transportation Final Report on Contract DOT-FR-00017 by Terraspace, Inc., February 1971.